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The ILSE Experimental Program (*)(**).

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Summary. — The Heavy-Ion Fusion Accelerator Research Program at Lawrence Berkeley Laboratory has proposed building a 10 MeV induction linac systems experiment, ILSE, to investigate accelerator physics and beam manipulations which are needed or desirable for an induction linac driver. This paper describes the experiments proposed for ILSE: transverse beam combining, drift compression, bending of space-charge-dominated beams, final focus, recirculation, and some studies of beam propagation in the environment of the reactor chamber.

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1. Introduction.

The proposed ILSE accelerator (described by Bangerter *et al.* in these proceedings) would provide the means to test at relevant scale most of the beam manipulations needed in a heavy-ion fusion induction linac driver. These manipulations include transverse beam combining, drift compression, bending of space-charge–dominated beams, final focus, recirculation, and some studies of beam propagation in the environment of the reactor chamber. One possible layout for the experiments is shown in fig. 1.

The ILSE accelerator design consists of a 2 MeV 4-beam injector, followed by a matching system into an electrostatically focused induction linac. Each beam will enter the linac with charge per unit length of 0.25 μC/m, major radius of 2.2 cm, and

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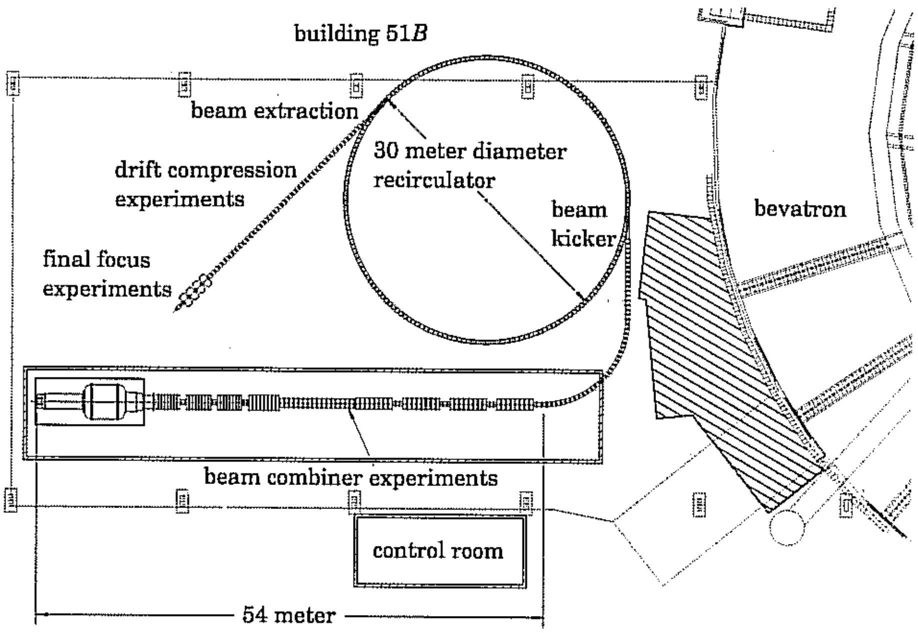

Fig. 1. – Possible layout of the ILSE experiments.

pulse length of 1 μs. Except for the short pulse length, these parameters are those of present driver designs. At 5 MeV the four beams can be combined transversely into one with four times the line charge density, which will be then be accelerated through a magnetically focused induction linac to 10 MeV. Again, the diameter and charge per unit length of the beam will be similar to what would be found in the magnetically focused section of a driver before longitudinal compression. The undepressed betatron phase advance per lattice period and the beam perveance will also be kept in the range appropriate for a driver, making the beams space-charge dominated. Because of these similarities to a driver, many driver issues can be addressed directly using the ILSE beams. However, because of the vast difference in final energy, experiments such as the final focus must be designed to properly model the driver in a scaled fashion.

It should be noted that the ion mass used in ILSE ($Z = 39$ for K^+) is much less than a driver ion. This does not affect the accelerator design, which is based in both cases on keeping maximized, and therefore approximately constant, the quantity σ_0, the betatron phase advance per lattice period ignoring space charge. Thus decreasing the ion mass decreases the magnetic fields necessary in the magnetically focused accelerator, but beam dynamics will be similar to the driver, since the depressed and undepressed betatron tunes will be similar to the driver.

2. – The experiments.

2·1. *Transverse beam combining.* – A heavy-ion fusion induction linac driver is likely to make use of transverse beam combining in order to reduce the costs of beam transport. However, transverse emittance will grow as a result of this process. The

ILSE combining experiment will be used to establish whether the emittance growth due to combining is acceptable at driver scale.

Emittance growth due to transverse merging of beams has been studied analytically and numerically [1], and, to a certain extent, experimentally [1,2]. As the beams merge, the strong space charge forces cause much of the emittance growth, as the four beams expand quickly (in $\sim 1/4$ of a plasma period) into empty spaces between beams. 2D PIC simulations predict that the normalized emittance in ILSE will increase from about $1\,\pi$ mm mrad to about 8–$10\,\pi$ mm mrad due to combining. Since the ion used in ILSE will be K^+, this should be scaled to find the emittance for the heavier mass of a driver. The result is a final emittance of about $5\,\pi$ mm mrad for the driver. Present final focus designs indicate that normalized emittance of about $8\,\pi$ mm mrad is acceptable.

The increase in emittance depends on the spacing between the beams when they emerge into the common focusing channel. This spacing must be minimized by bending the trajectories of the individual beam centroids upstream. This is accomplished with a beam «combiner» consisting of alternating dipoles and focusing quadrupoles. The effects of both field and chromatic aberrations must be considered in the combiner. Since the beams will have a velocity difference from head to tail (referred to below as a velocity «tilt»), all designs are first-order achromats. A velocity tilt of up to $\pm$ 10% has been allowed for. Second- and third-order chromatic effects are not a problem for the combiner, largely because they are of opposite sign and tend to cancel.

Field aberrations occur as a result of the fact that as the beams progress through the combiner their centroids converge, leaving less space between the beams for focusing electrodes. For the round electrodes used in the electrostatically focused accelerator the electrode radius must be $8/7$ times the aperture radius to eliminate the lowest-order nonlinear field component, the dodecapole. So, as the space for electrodes diminishes, more innovative electrode shapes must be used in order to minimize nonlinearity. The emittance growth due to field aberrations in the combiner is of little importance, since the emittance growth due to the merging process itself is much larger. The effort to reduce field aberrations in the combiner is directed at minimizing beam loss. Preliminary designs for the combiner have been devised, and their effects on the beams are being examined using 2D PIC simulations that include realistic image forces in quadrupole and drift spaces, accurate 2D field aberrations for the quadrupoles, and beam-beam forces. (Aberrations and image forces in the dipoles are not modeled yet.) At this point these designs show beam loss of 7%.

As can be seen from the above discussion, combiner issues involve transverse physics. Since the ILSE beams are at full driver scale in the transverse plane, beam dynamics will be the same as for the driver.

2·2. *Drift compression.* – Current driver designs include longitudinal compression of the beams by about a factor of 10 after they emerge from the accelerator. Because of the flexibility of the ILSE accelerator, this drift compression can be explored over a wide range of parameters. The beam pulse length can be varied from 0.5 to 2 μs, the velocity tilt from 0 to 10%, and the current from 0 to 8 A. Of great interest in these experiments will be any growth of longitudinal or transverse emittance. Previous simulations [3] have shown that, if the proper head-to-tail velocity profile is applied, final transverse and longitudinal emittance are adequate for the final focus system. In ILSE, as in a driver, drift compression takes place while the beam is being bent and, subsequently, sent through the final focus system. The bend can couple longitudinal and transverse emittance, and the attempts in both systems to deal with chromatic effects are challenged by the velocity and current variations along the beam.

Among the drift compression experiments presently planned for ILSE are 1) an experiment with parameters scaled from the driver, and 2) compression of the full current (8 A). The first experiment would involve using about 8% of the full current, with a tilt of $\sim$ 2–5%, to compress the beam by a factor of 10. This is an exact scaling of the longitudinal fluid equations from a driver, and would test driver beam physics in a scaled fashion. The second experiment would use the full tilt available, 10%, to compress the beam by a factor of 2. Because of the low kinetic energy and comparable space charge forces of the beam relative to a driver, the compression is much less than in a driver for this case.

2'3. *Bending.* – Most driver and target concepts require the ability to bend high-current, high-energy heavy-ion beams in order to orient them to the reactor configuration. This requirement is complicated by simultaneous longitudinal drift compression, which requires a head-to-tail velocity tilt of 2–5% of the mean velocity. Therefore, significant chromatic effects are expected and must be controlled with sufficient precision for final focusing to be effective. In ILSE, as in the driver, this control is achieved through achromatic design, which takes into account the large image forces and hoop stresses associated with the high ion current. Since the beam current increases with distance along the beamline, the aperture of beamline elements must be selected to accommodate centroid dispersion as well as increasing beam radius.

Experiments on the effect of space charge upon bending are of greatest interest with the full 1–2 μC/m line charge density. Here the largest longitudinal and image forces occur, and space-charge–induced aberrations can be examined in their most extreme form.

As presently envisioned, the ILSE bend would be a 180° arc of 9 m radius. This would transport a 10 MeV beam of ions with mass up to 39 a.m.u., 10% velocity tilt, and 2.0 μC/m line charge density (after compression). To fit both the bends and the quadrupoles into the constricted lattice period, a combined (or overlaid) arrangement of their magnetic fields may be required. In some designs, quadrupole field strengths are as high as 2.5 T at the wire, but the bend fields are about 0.5 T. These magnets would be pulsed for milliseconds to avoid excessive heating, and little or no iron for field shaping would be employed. An achromatic layout (one that gives first-order cancellation of off-momentum effects) may be achieved, for example, by designing the lattice with five-cell blocks having a 360° phase advance per block. Bends of equal strength would overlay the F and D quadrupoles, and half-strength bends would be used in matching sections at the ends of the bend system. Because of space limitations, the curvature of the bend is stronger than that of a driver (ratio of bend radius to lattice period is half that expected for a driver), but the bend layout and the transverse dynamics, including the tune shift due to image forces, will be very similar to a driver.

Exploring the conditions for maintaining low emittance and centroid control are the objectives of the bend experiment. Particle-in-cell simulations performed with the 3D PIC code Warp indicate that, with proper design, unwanted emittance growth and other disturbances within the beam pulse can be held to a tolerable level [4]. However, the simulations have indicated a coupling of longitudinal and transverse emittance, as well as coupling of dynamics between the horizontal and vertical planes. These phenomena, if borne out by experiment, could place bounds on the allowable longitudinal momentum spread.

2·4. *Final focus.* – As is well known, the transverse beam emittance limits the focal spot radius produced by the final focus system to

$$r \geqslant \frac{\varepsilon_n}{\beta\gamma\theta}\,, \tag{1}$$

where ε_n is the normalized emittance, $\beta = v/c$, γ is the relativistic Lorentz factor, and θ is the half-angle of the beam focal envelope. The maximum value of θ is typically constrained by third-order geometric and second-order chromatic aberrations, but the limit has not been precisely established. The effect of aberrations can be easily estimated via the paraxial envelope equations and codes that solve these equations. However it is hard to quantify the effects of aberrations that are higher order in bend angle and therefore left out of paraxial codes. The role of space charge on aberrations is also largely unknown (beyond lowest-order approximations) at present. The role of the ILSE final focus experiments will be to investigate the influence of aberrations on final spot size, the effect of initial beam parameters on aberrations and position of the focus, and proposed systems and remedies. The magnitude of chromatic aberration effects has been calculated for sample focusing systems, and found to place stringent limits ($\leqslant \pm 0.5\%$) on the longitudinal momentum spread of the beam. The addition of sextupoles and dipoles to correct chromatic aberrations in the final focus, and thus relax this longitudinal emittance constraint, will be explored.

Several final focus experiments are envisioned. One will be a scaled experiment, with energy, emittance, and all dimensions scaled exactly from a driver. Particle trajectories, applied fields (including aberrations), and space-charge fields would be exact scaled replicas of those in a driver's final focus. The final focus configuration generated by Wollnik for the HYBALL II study [5] ($A = 200$, $\beta = 1/3$, $\varepsilon = 30\pi$ mm mrad) can be reproduced precisely with ILSE parameters if the quadrupole fields are

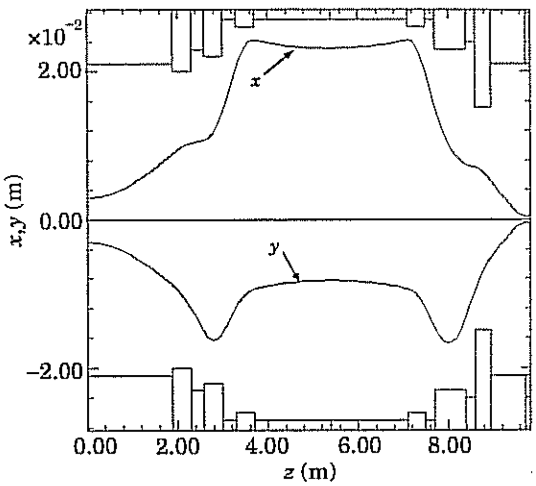

Fig. 2. - Beam envelopes for the ILSE final focus scaled experiment.

reduced by a factor of 80 and the current is reduced by a factor of 6400. These scalings can be accomplished by collimating the 2.5 cm, 8 A ILSE beam down to 0.3 cm and 0.1 A, assuming uniform current in the ILSE cross-section. A sample layout and resultant beam envelope for the scaled experiment as calculated by the 2D PIC code FOCI are shown in fig. 2. The mean radius of the beam as it exits the accelerator is 3 mm, and the emittance is $3 \cdot 10^{-6} \pi$ mrad. The quadrupole apertures are about 2.5 cm, and all fields are less than or equal to 0.3 T. The focal spot will have a radius of 0.35 mm.

Focusing the full ILSE beam (8A) is also planned. In this case the magnet apertures and fields are an order of magnitude larger than in the scaled experiment, as is the beam spot. The final focus system is 5.3 m long. Neutralization of the beam after the focus is of interest. If neutralized, the beam will ballistically converge in an additional 0.56 m. Initial emittance in this case has been assumed to be 30π mm mrad.

2·5. *Recirculation.* – The proposed site for ILSE would allow a recirculator ring diameter of between 30 and 100 m. A considerable increase in the ion energy—to energies approaching 100 MeV—would be possible. Such a recirculator could address most of the main issues of recirculation: synchronization of pulsers and dipoles with the beam, injection and extraction, and emittance growth. Vacuum studies—beam interaction with gas, and gas desorption from the walls—could be done, but only for the relatively low current and kinetic energy of the ILSE beam. The recirculator would also provide greater effective length for the accelerator, enhancing studies of accelerator issues such as halo generation, propagation of longitudinal waves on the beam, and longitudinal error correction. Positive feedback may be used to enhance the growth of longitudinal waves, since otherwise, due to the low current of the ILSE beams, growth is too small to be measured.

2·6. *Reactor chamber propagation.* – Although the energy of the beamlet will be too small to allow interesting target studies, beam propagation into partial vacuums such as might exist in the reactor chamber is a possible subject for study with ILSE. Conditions for achieving beam neutralization in the target chamber will also be investigated. Beam neutralization may be required for the high-current ($A/q \leqslant 100$) fusion driver designs.

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